AN INVESTIGATION OF THE POTENTIAL FOR RESIDUAL STRESS MEASUREMENTS DURING SUBMARINE HULL FABRICATION

(2)

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MRL-TR-93-8

AR-008-265

SEPTEMBER 1993

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An Investigation of the Potential for Residual Stress Measurements During Submarine Hull Fabrication

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M.Z. Shah-Khan, N.J. Baldwin, D.S. Saunders and D.H. Sanford

MRL Technical Report
MRL-TR-93-8

Abstract

In this technical report the suitability of resistive strain sensors was evaluated with particular reference to the monitoring of residual stresses during welding construction of submarine pressure hull and during seabound operation of a submarine. Adhesively bonded and weldable strain gauges were tested in the laboratory for suitable characteristics and against specific requirements. The requirements were (a) ease of installation (b) survivability in high temperature environment (c) reliability in gauge signal and (d) ease of instrumentation to data logging system and calibration. Experiments which were designed to evaluate these requirements are described. The characteristics and fundamentals of the adhesive and weldable gauges explored during these experiments are discussed. Quantitative data in terms of strain gauge signal were determined following each stage of experimentation. The magnitude of strain gauge signal, when converted to equivalent stress units, provided an accurate measure of stress levels in the test plate. The results indicate that it is possible to implement structural monitoring starting from welding fabrication to service operation for the Collins Class submarine using resistive strain gauges.

DEPARTMENT OF DEFENCE
DSTO MATERIALS RESEARCH LABORATORY

Published by

DSTO Materials Research Laboratory
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Victoria, 3032 Australia

Telephone: (03) 246 8111
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AR No. 008-265

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N.J. Baldwin

Nick Baldwin originally trained as a Mechanical Engineer and is now a Senior Professional Officer currently engaged in welding research, stress monitoring and fatigue testing of welded components at MRL. Over the 24 years of service at MRL, Nick has attained and applied a broad range of disciplines which include mechanical testing, instrumentation, penetration mechanics, fatigue testing, calibration, equipment design, Stirling Engine evaluation and component failure consultation.

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Darren Sanford

Darren Sanford graduated with a Bachelor degree in Mechanical Engineering in 1990 from Ballarat University College. He commenced his employment at MRL in 1991working in the Specialised Instrumentation Group to work on the development of the capability to measure strain on a variety of naval vessels. Specific activities included measurement of hydrodynamic loads of vessels in rough sea states and strain measurement in relation to carbon fibre crack patching of HMAS Sydney.

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An Investigation of the Potential for Residual Stress Measurements During Submarine Hull Fabrication

1. Introduction

The pressure hull of the Australian Collins Class submarines (Kochums Type 471) is being fabricated from a new, high strength quenched and tempered steel, designated BIS 812 EMA. This steel is similar to submarine construction steels of the HY class. It has a low carbon content and is lean in alloying elements resulting in the steel's good weldability and low temperature fracture toughness properties. Work at MRL has contributed to an extensive study of the metallurgy and mechanical properties of this class of steel, the welding consumables and aspects of fabrication processes. Extensive work has also been conducted on the fracture properties of the parent and welded plate, and has included response to explosive loads, fracture toughness, fatigue and corrosion fatigue crack growth behaviour (reviews by Shah Khan *et al.* (1992, 1993a) and Ritter *et al.* (1991a, 1991b)). MRL currently has an active involvement in the development of life prediction methodologies for structural details of the submarine and these methodologies utilise fracture property data and a knowledge of the stresses generated within the structure by normal welding and fabrication procedures.

Fatigue crack growth studies and fatigue life estimation of the submarine structure are necessary because of the particular operational environment under which the submarine operates. Fatigue loading arises because the compressive stresses, due to the changing operational depth of the submarine, are superimposed on the tensile residual stresses within the structure. In addition, flutter loading due to noise and vibrations from operating machinery also contributes to fatigue loading (Fig. 1).

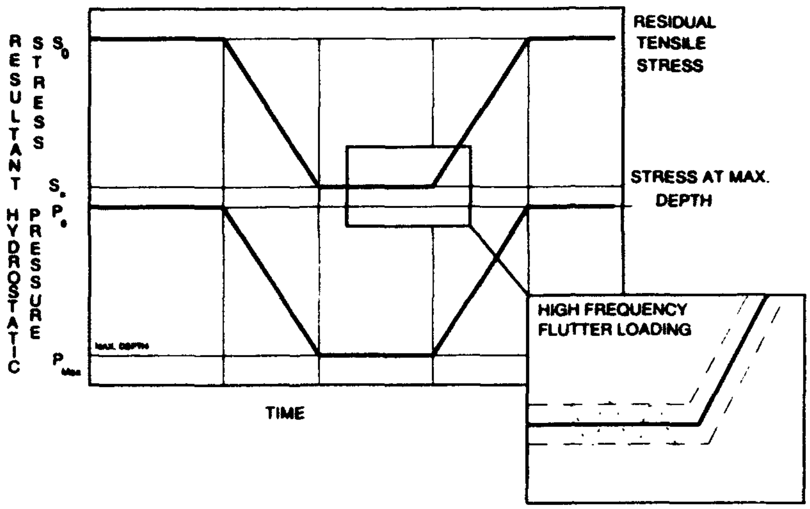

Figure 1: A schematic representation of a loading cycle of a submarine and the resulting changes in stress level in a welded element with a tensile residual stress, from Shah-Khan et al. (1993b).

Two important factors which may significantly influence the fatigue life predictions when using fracture mechanics methodologies are the accuracy of the

(1) crack growth data, and
(2) estimations or measurements of applied stresses and residual stresses within the submarine structure.

The crack growth data can be determined from coupon or specimen testing programs (which may incorporate environment, residual stresses, load spectrum effects, etc) and from structural detail testing programs which may also incorporate the above-mentioned effects, see Shah-Khan *et al.* (1992 and 1993a) Kilpatrick (1986) and Sumpter (1991).

The estimation of the applied stresses within the submarine structure presents a significant challenge and one which is currently under investigation. These stresses may be determined analytically (see the reviews by Kendrick (1964) and Robertson (1990)) or determined by finite element methods. These stresses are generated from the loading of the hull and pressure bulkheads by the hydrostatic pressure at operational depths. The magnitude and distribution of these resultant stresses within the submarine structure is complicated considerably by the presence of residual stresses derived from the welding and fabrication process. Estimating the magnitude of residual stresses from the welding process is virtually an intractable problem although the limited application of finite element methods has produced residual stress distributions for some submarine structural details as shown in Figure 2, Kilpatrick (1983) and Smith and Kilpatrick (1991).

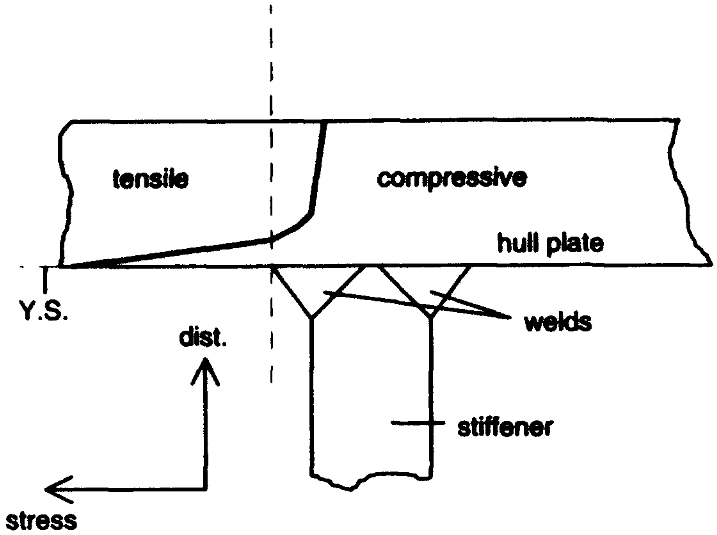

Figure 2: A schematic diagram showing the change in residual stress in the hull plate near a ring stiffener, Kilpatrick (1983) and Smith and Kilpatrick (1991).

The effects of these stresses must be taken into account when fatigue life estimates are necessary as well as the additional modifications to the stress patterns due to specific structural details such as ring stiffeners, bulkheads (thickened plates), junctions, attachment points and penetrations. Much work has been undertaken in testing scale models fabricated using the same welding and fabrication technologies as the full-sized structures, however, *it has been reported* that small-sized models develop different levels of residual stress than the full-sized models, Kilpatrick (1983) and Burnside *et al.* (1986). It is therefore appropriate that measurements of residual stresses are undertaken on an actual submarine hull. It is also important to determine the changes in residual stresses with operation, since it is not known to what degree welding residual and manufacturing stresses "shakedown" with submarine operation. Shakedown is a phenomena where changes in residual stress pattern occur within the submarine during the first few dives. Continued through-life monitoring is therefore desirable, however if this is not practical, monitoring should at least be conducted during the early life of the submarine.

It is well known that the susceptibility of steels to corrosion fatigue increases with increasing strength and was therefore one of the more significant factors investigated during the development of the steel for the Collins Class submarine. Crack growth data for a range of candidate submarine hull steels has been generated by experiments on the parent plate and the weld metal in both the laboratory air and marine environments, Jones (1981, 1982) and Gill and Crooker (1990). Furthermore, detailed testing of the actual production steel, BIS 812 EMA, used in the Collins Class submarine has been undertaken, Shah-Khan and Burch (1990, 1991, 1992, 1993a). This work also includes studies of the effect of superimposed flutter loading on fatigue life. These data can be readily incorporated into the fatigue life models which are presently under development at MRL.

The abovementioned crack growth data, which is used in some life prediction calculations, are generated as da/dN vs ΔK plots, usually from centre cracked or compact tension type fracture specimens. Provided the stress intensity factor (more correctly ΔK) can be determined at a location within a submarine structure, it is then possible to predict the growth of a crack from defects such as inclusions, welding and surface defects. However, residual stresses can significantly alter the ΔK seen by the crack tip and therefore influence crack growth rates , Vosikovsky (1978).The methodologies for life prediction will not be discussed in this report as it has been dealt with elsewhere, see Gerberich and Gunderson (1982) and Shah-Khan *et al.* (1992). The main concern in the present work therefore is the estimation of residual stress arising from welding and fabrication.

The construction technique for the Collins Class submarine uses the conventional method of welding pre-fabricated "can" sections to form the complete structure. The individual "cans" are fabricated from roll-formed (curved) plates and reinforced with ring stiffeners at regular intervals. A typical fabricated section is shown in Figure 3.

Figure 3: *Submarine construction using welded can sections.*

This report addresses the challenge in measuring stress within a submarine structure, and outlines a preliminary approach for the implementation of a strain gauging system for monitoring residual stress levels during (a) construction, (b) shake-down and (c) through-life. It is believed that this form of structural monitoring has not been proposed for the Collins Class submarine structure.

2. *Objectives*

The objective of the task was to implement an experimental program to demonstrate that

(1) Welding-induced residual stresses can be measured,
(2) Changes in residual stress during submarine operation can be measured, and
(3) Stability of strain gauges is satisfactory for long term data logging.

3. *Experimental Approach*

The experimental program has been undertaken in the following three phases:

3.1 Phase I

Selection of strain gauges (bonded or weldable), adhesives, cabling, protective coatings etc, that are capable of surviving at 200°C and investigation of suitable instrumentation to carry out strain measurement.

The work in the selection of suitable strain gauges, adhesives and protective coating, and the design of strain gauge layout and cabling was carried out in conjunction with the Specialised Instrumentation Section of the Scientific Services Division (MRL). The selection of the gauges and recommended method(s) of installation are detailed in the report by Wells et al. (1991). The development of instrumentation and data logging methodologies was undertaken with the assistance of the Engineering Services Division (MRL).

3.1.1 Selection of Strain Gauges, Adhesive and Protective Coating.

The two strain gauge types selected for the study were the Micro Measurement adhesively bonded strain gauge type WK-06-500WT-350 and the Micro Measurement weldable gauge type LWK-06-W250D-350. They were rosettes each comprising of stacked and unstacked right angled pairs of resistive strain gauges respectively. The gauges were selected for their reported ability to withstand temperatures of up to 260°C (weldable gauges) and 290°C (adhesive gauges) for extended periods of time. Similarly the adhesive, Micro Measurement M-Bond 610, was chosen for its reported high temperature performance.

The coating used to protect both types of the strain gauges against moisture, shipboard chemical environments and physical damage consisted of an initial coating of M-COAT C followed by a top coating of 3145 RTV. For long term exposure and when temperatures are likely to reach 260°C the combination of M-COAT C and 3145 RTV is recommended.

3.1.2 *Selection of Data Acquisition System*

It is proposed to monitor a large number of channels on the Collins Class submarine (Wells 1991) and therefore, the data acquisition system, selected or designed, must have the necessary capability. The interest in this current research program is for static measurements of changes in residual stress at specific locations during construction, and during the first few dives. Therefore measuring systems such as a data logger and a depth monitor are considered appropriate. The instrumentation must be compact due to spacial constraints within the submarine. It is desirable to have the instrumentation driven by a PC for ease of use, data retrieval and data manipulation, and for programing the system to enable data to be collected at predetermined time intervals over a specified period. Another consideration is that the instrumentation is required to have differential amplifiers and filters for noise reduction, as a submarine environment is electrically noisy and long leads from gauge to instrumentation may need to be used.

For the laboratory evaluation, a data logger (DATATAKER 500®) connected to a PC laptop was used and is considered suitable to carry out static stress measurements during submarine construction. For stress measurements during submarine diving operation, a depth monitor can be utilised and then instructing the DATATAKER 500® to measure changes in residual stresses with depth. The DATATAKER 500® is a microprocessor capable of monitoring low-level signals through 10 differential or 30 single-ended analog input channels. The DATATAKER 500® was monitored from a Toshiba T1600® lap-top computer using D-TERMINAL® software (Data Electronics of Australia Pty Ltd).

3.2 *Phase II*

Work in this phase investigated methods for installing the recommended strain gauges to the BIS 812 EMA plate and their connection to the instrumentation. A fixture for the application of pressure to the gauges during adhesive bonding was developed as well as a technique for spot welding the gauges bonded to the metal foil. To ensure a dimensionally stable test plate, a 35 mm thick BIS 812 EMA steel plate, 500 mm by 312 mm, was held at 300°C for 48 hours with the plate sandwiched between Cooper heater blankets and insulation bricks. It was considered that this heat treatment established a dimensionally stabilised plate and therefore any changes in strain gauge signal would be due to externally applied stresses or residual stresses introduced during the welding process.

Strain gauge installation, for both bonded and welded gauges, is one of the critical stages of any gauging process and requires care in both surface preparation and gauge installation procedure. Adhesive and weldable rosettes were alternately installed along the centreline of the test plate, the disposition of the gauges is shown in Figure 4.

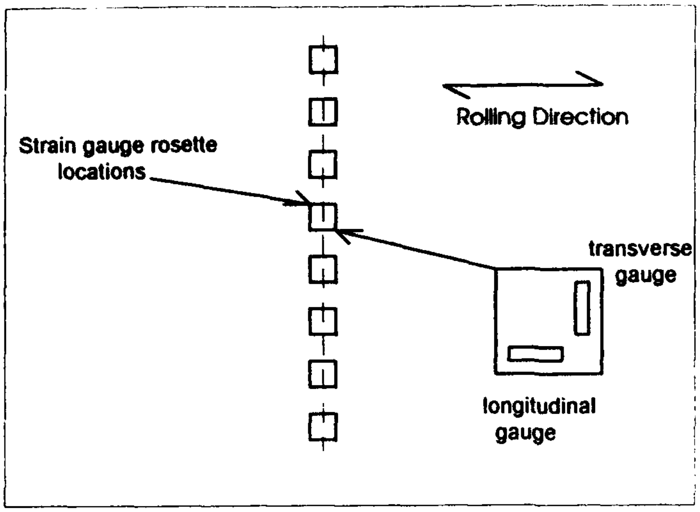

Figure 4: Schematic diagram showing the strain gauge locations.

The gauges were divided into two lots (see Table 1) using an alternating sequence of adhesive and weldable rosettes. Each lot therefore consisted of two adhesive and two weldable rosettes, making 8 strain gauges in each lot. The strain gauges aligned parallel to the rolling direction of the plate measured longitudinal strain, while the gauges aligned transverse to the rolling direction measured transverse strain. Such a configuration is commonly used for residual stress measurement.

Table 1: Strain gauge designation, type and orientation

LOT # 1 (L1)	Orientation	Gauge Type	LOT # 2 (L2)
Gauge #			Gauge #
L1G1	Longitudinal	Welded	L2G9
L1G2	Transverse	Welded	L2G10
L1G3	Longitudinal	Adhesive	L2G11
L1G4	Transverse	Adhesive	L2G12
L1G5	Longitudinal	Welded	L2G13
L1G6	Transverse	Welded	L2G14
L1G7	Longitudinal	Adhesive	L2G15
L1G8	Transverse	Adhesive	L2G16

3.2.1 *Adhesively Bonded Strain Gauges*

Bonded type gauges, WK-06-500WT-350, were attached using M-Bond 610 epoxy resin adhesive, in accordance with the procedure outlined in the Micro Measurements Instruction Bulletin B-130-14 (Micro Measurements (1979)). The strain gauge adhesive was initially cured under an applied pressure of 0.3 MPa at 165° C for 2 hours. A method for applying pressure was developed to expedite the installation process and can be adapted for the submarine task. Pressure was applied to each gauge area by a fixed deflection calibrated spring which forced a circular pressure platten onto the silicon rubber covered gauge area. Four of these pressure plattens were simultaneously loaded by one beam which was held at a fixed distance from the plate surface, as shown in Figure 5.

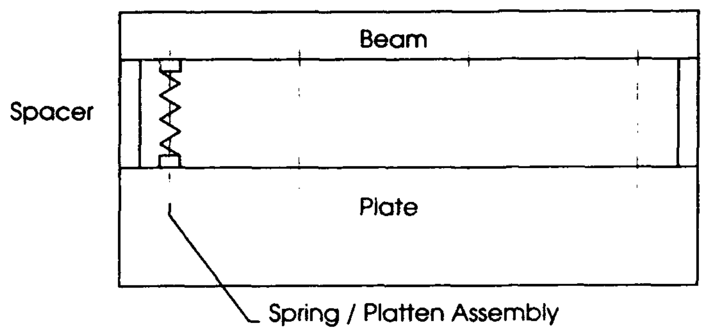

Figure 5: Schematic diagram showing pressure application method during adhesive gauge application.

The loading beam can be positioned by magnetic clamps on the submarine hull, or by bolts as used in the laboratory experiments. Following the initial curing at 165°C, the gauges were then post cured without the applied pressure at 205°C for a further two hours as specified by the gauge manufacturer. Following the installation of adhesive strain gauges, one gauge (L1G7) failed to give an output signal due to damage to its terminal, however the remaining gauges were found to be functional.

3.2.2 *Spot Welded Strain Gauges*

Weldable strain gauges, type LWK-06-W250D-350 (rosette in planer configuration), were installed in accordance with the procedure outlined in the Micro Measurement Instruction Bulletin B-131-4 (Micro Measurements (1975)). Additional information on the installation of welded gauges was communicated by Robertson (1992) who cited DRA experience with welded strain gauges. A portable capacitive-discharge welding unit was employed to attach pairs of right-angled strain gauges on the steel plate. Figure 6 shows the capacitive-discharge welding unit and the spot weld electrode. The electrode had a spherical tip approximately 0.8 mm diameter.

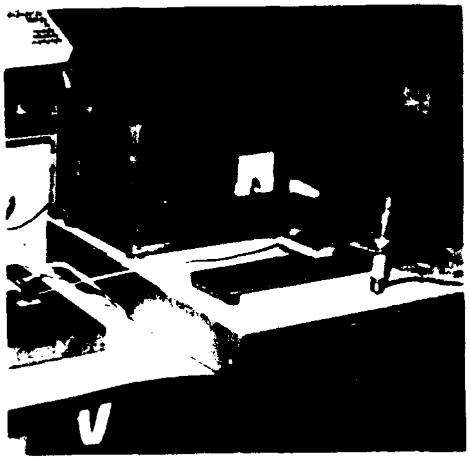

Figure 6: *Capacitive-discharge welding unit and spot welding electrode tip*

An optimum energy level for welding was determined by performing spot welding trials on a sample metal carrier. Each rosette was attached by approximately fifty spot welds in the configuration recommended in Bulletin B-131-4 (Micro Measurement 1975).

3.2.3 *Terminal Tabs*

Once the gauges were installed, bondable terminal solder tabs were bonded to the test plate adjacent to strain gauge rosettes. The curing of solder tabs was carried out at room temperature (21°C) for 48 hours under the recommended pressure. This procedure was different from that recommended in Micro Measurement Instruction B-130-14 (1979). During subsequent testing it was found that the adhesion of solder tabs to the test plate was unsatisfactory particularly after the thermal cycle trials. New tabs were substituted whenever tabs were found to come unbonded. The substituted tabs were left unattached to the test plate.

3.2.4 *Connection of Gauges to the Data Acquisition System*

In order to measure the output of the strain gauges, each gauge was connected into a Wheatstone bridge. This consisted of a quarter bridge arrangement, i.e. one active 350 Ω strain gauge and three 350 Ω (± 0.1%) precision resistors to complete the bridge as shown in Figure 7. The gauges used were of self-temperature-compensated type. Wiring from the gauge to the Wheatstone bridge was kept short (25 to 50 mm) and all measurements were carried out at room temperature. It was therefore felt that it was not necessary to compensate temperature by means of compensation gauges (dummy gauges).

A 10 volt excitation was supplied to the Wheatstone bridge from a Scientific Electronics Regulated Voltage Supply. The output from the Wheatstone bridge was connected to the DATATAKER 500®. However, the data logger does not have a means of initially balancing the bridge, therefore a small offset voltage occurred at zero load or zero strain.

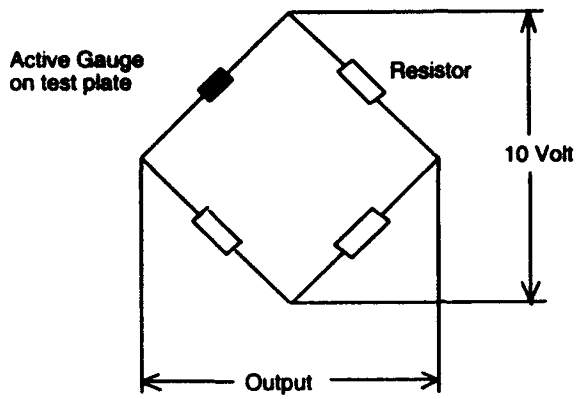

Figure 7: Schematic diagram of the strain bridge.

For the submarine application, it was proposed that connecting wires be removed after the initial zero measurements had been made from all gauges . Metal protective covers could then be placed over the gauges. For subsequent measurements these covers be removed and the lead wires reconnected by soldering.

3.3 Phase III

In this phase, several related small experiments were carried out to assess:

(a) Strain gauge zero stability.
(b) The effects of resoldering lead wires.
(c) The effects of thermal cycling on gauge survivability and performance.
(d) Effect of spot welds on the fatigue life BIS 812 EMA .
(e) A method of calibrating the strain gauge output in terms of stress.
(f) Measurement of residual stresses due to several weld passes.

Table 2 outlines the nine stages of experimentation and corresponding test conditions. After each stage the gauge signals were measured and the changes in zero load signals were recorded. Gauge signals were also measured when subjected to a 0 to 125 kN simple bending moment load and their span calculated following stages 1, 3 and 4.

Table 2: Summary of the stages in signal measurements

Stage 1	After gauges installed
Stage 2	After protective coating
Stage 3	After 48 hrs at 300/200°C
Stage 4	After 2 hrs at 200°C
Stage 5	After 1st welding pass
Stage 6	After 2nd welding pass
Stage 7	After 3rd welding pass
Stage 8	After 4th welding pass
Stage 9	After 5th welding pass

The gauge signals were converted to equivalent stress by equating the change in signal (mV) to the maximum outer fibre stress in the plate (MPa), see § 3.3.4.

3.3.1 *Gauge Stability at Zero Load*

The stability of the strain gauges was checked by measuring the signal of each gauge at zero load prior to and after every stage in the experimentation.

3.3.2 *Effects of Desoldering and Resoldering Gauge Connections.*

Experiments were conducted to assess changes in strain gauge bridge signal associated with the repeated desoldering and resoldering of the bridge leads. This procedure is necessary to minimise interference of connecting wires and supporting equipment with the submarine construction. The subsequent reconnection of the bridge leads can alter the resistance of the connection, and since the Wheatstone bridge is sensitive to such variation, an apparent strain reading will be registered, which unless it is measured would lead to an erroneous result.

3.3.3 *Effects of Thermal Cycling*

Thermal cycling was undertaken to investigate the survivability and signal stability of strain gauges and the integrity of the bond. The cycles simulated the pre-heating and heating associated with the welding processes during the submarine construction. A typical thermal cycle would last 1 to 3 days. The gauges were assessed by measuring the zero load signal before and after each cycle, and also by measuring the gauge signal during step-loading of the test plate in four-point bend mode.

3.3.4 *Calibration of the Strain Gauges*

Strain gauges were calibrated by subjecting the plate to four- point bending load (Fig. 8) ranging from 0 kN to 125 kN. Each strain gauge signal (mV) was converted to stress (MPa).

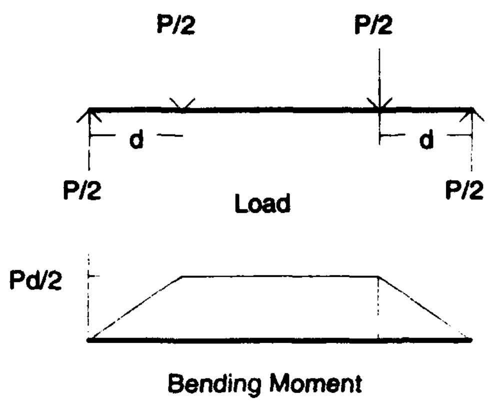

Figure 8: Load and bending moment diagrams

Incremental loads were applied up to 125 kN. In the above loading mode and for the plate geometry used, the bending moment and the outer fibre stress are given by equations (1) and (2) respectively.

Bending Moment	$M = Pd/2$	(1)
Outer fibre stress	$\sigma = My/I$	(2)

where,

P = Load in Newtons
y = Distance from neutral axis to outer fibre
= D/2 (where D = plate thickness)
I = Moment of inertia = $BD^3/12$
where B = plate width

Using the above equations, for a maximum load of 125 kN acting on a moment arm (d) of 175 mm (D = 35 mm, B = 312 mm):

Bending moment	= 10937 Nm
The maximum theoretical outer fibre stress	= 172 MPa

Using $\sigma = \varepsilon E$ and a You.. ;s r odulus (E) of 210000 MPa

The maximum theoretical outer fibre strain = 818 $\mu\varepsilon$

For the purposes of illustration, in a later section of this report, the gauge signals in mV were converted to Equivalent Stress in MPa. This gives a quantitative measure of the shift of the residual stress data caused by extraneous changes in gauge signals.

3.3.5 *Weld Induced Residual Stresses*

In these experiments, submerged arc welding passes were carried out at 50, 100, 150 and 200 mm from the gauges. The input energy for each pass was 2.0 kJ/mm and the direction of welding was normal to the longitudinal direction (rolling direction) of the test plate. Table 3 shows a range of pre-heat plate temperatures and corresponding distances of weld passes from the centreline of the gauge. For these experiments, the closer the weld pass to the gauge centreline the lower the pre-heat temperature used. This was to insure that the post weld temperature of the plate, particularly at the gauge centreline, always remained at 200 (^{o}C) or lower. The build-up of residual stresses following each welding pass was recorded by measuring the change in zero load signal of the gauges.

Table 3: *Weld pass distances from gauges centreline, pre-heat and post weld plate temperatures*

Distance of weld pass from gauge centreline (mm)	Pre-heat temperature (^{o}C)	Post weld plate temperature (^{o}C)
200	185	200
150	175	195
100	160	200
50	160	190

3.3.6 *Effects of Spot Welding on Fatigue Life*

Fatigue tests were carried out in order to assess the effect of spot welds on the fatigue life behaviour of BIS 812 EMA steel. Preliminary testing, however, was carried out on an equivalent steel designated as RQT 701. Circular hourglass specimens with and without spot welds were tested in air to complete failure under cyclic loading, maximum cyclic stress being 753 MPa. The fractured specimens were examined under scanning electron microscope to determine whether the spot welds were the initiation sites for fatigue cracks.

4. Results

4.1 Effects of Desoldering and Resoldering on Zero Load Signals

The effect on zero load signals due to the desoldering and resoldering of lead wires connecting the solder tabs to the data acquisition system is shown in Table 4. The data in this table list measured bridge signals (mV) following each desoldering/resoldering of lead wires, active gauge in it being a longitudinal weldable type (L2G13).

Table 4: Changes in bridge signal with the active gauge being L2G13.

Reading No.	Step	Signal (mV)	Change %
1	Initial solder	-3.743	0
2	Resolder 1	-3.723	+0.5
3	Resolder 2	-3.718	+0.7
4	Resolder 3	-3.728	+0.4
5	Resolder 4	-3.740	+0.1
6	Resolder 5	-3.723	+0.5
7	Resolder 6	-3.721	+0.6
8	Resolder 7	-3.726	+0.4

The bridge signal varied between -3.743 mV and -3.718 mV, i.e. a maximum variation of + 0.7% . This is equivalent to a variation of approximately 1.0 MPa which for a 690 MPa YS steel is considered to be negligible and demonstrates that the repeated desoldering and resoldering processes are not of a major concern. However, it is good practice to use a consistent amount of solder for each junction thereby avoiding changes in resistance which affect the strain gauge signals.

4.2 Factors Affecting Zero Load Signals and Sensitivity of Gauges

For each of the experimental stages studied, see Table 2, the zero load signals are summarised at the end of section 4.2 in Tables 5 to 8 , and the 125 kN load signals (span) are summarised in Tables 9 to 12. The data are also presented graphically in Figures 9 to 16. In calculating the span signal, the bridge signal measured at zero load was subtracted from the signal measured at 125 kN. For clarity, longitudinal and transverse gauges are treated separately and each gauge is identified by its lot (L) number.

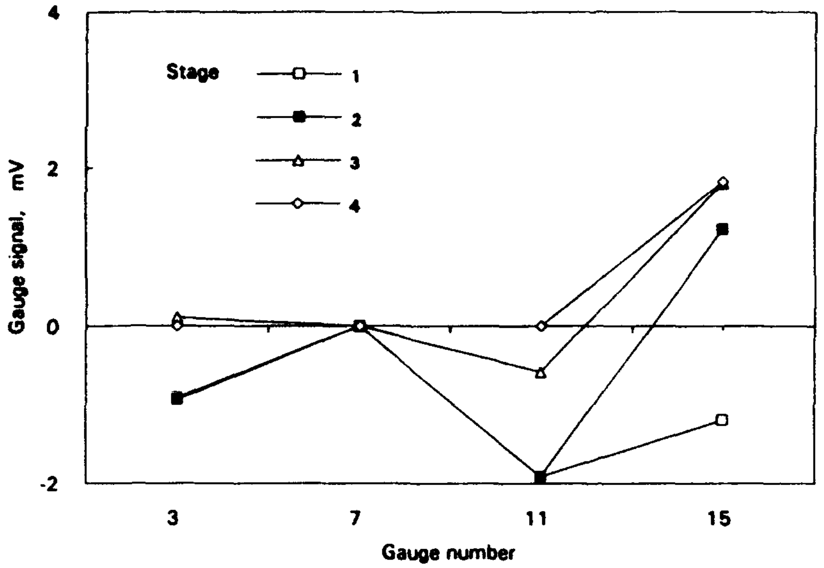

Figure 9: Zero load signals of adhesive longitudinal gauges L1G3, L1G7, L2G11 and L2G15. Gauge L1G7 was unserviceable after attachment. The reason for the large signal change from Stage 1 to Stage 2 in gauge L2G15 was unknown.

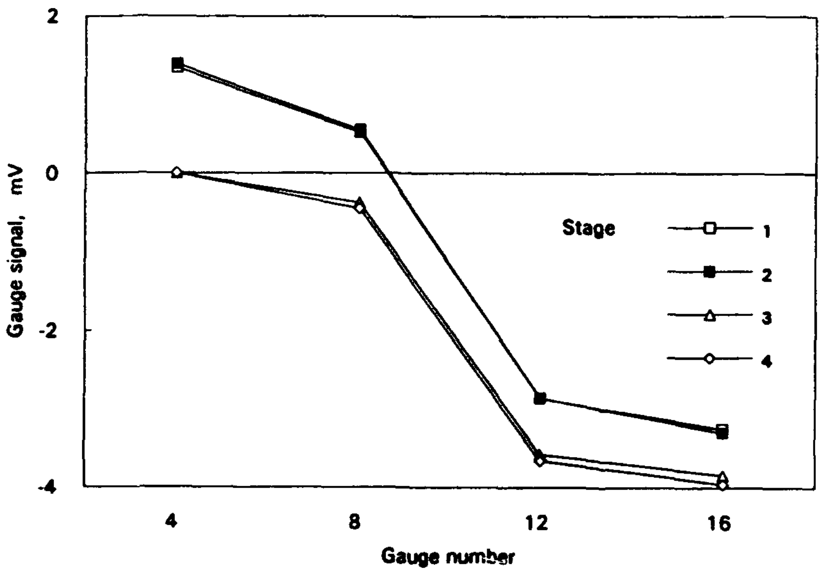

Figure 10: Zero load signals of adhesive transverse gauges L1G4, L1G8, L2G12 and L2G16. Note the changes in signals of the gauges from Stage 2 to Stage 3.

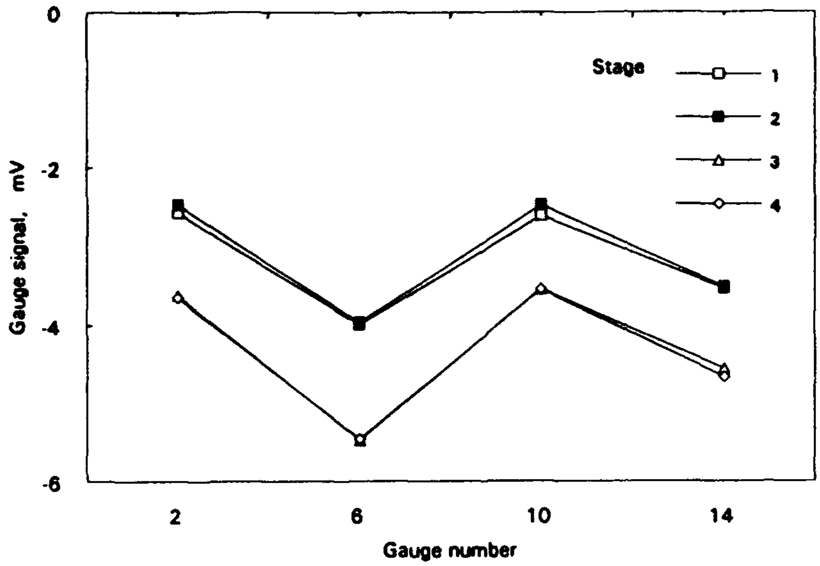

Figure 11: Zero load signals of welded transverse gauges L1G2, L1G6, L2G10 and L2G14. Note the changes in signals of the gauges from Stage 2 to Stage 3.

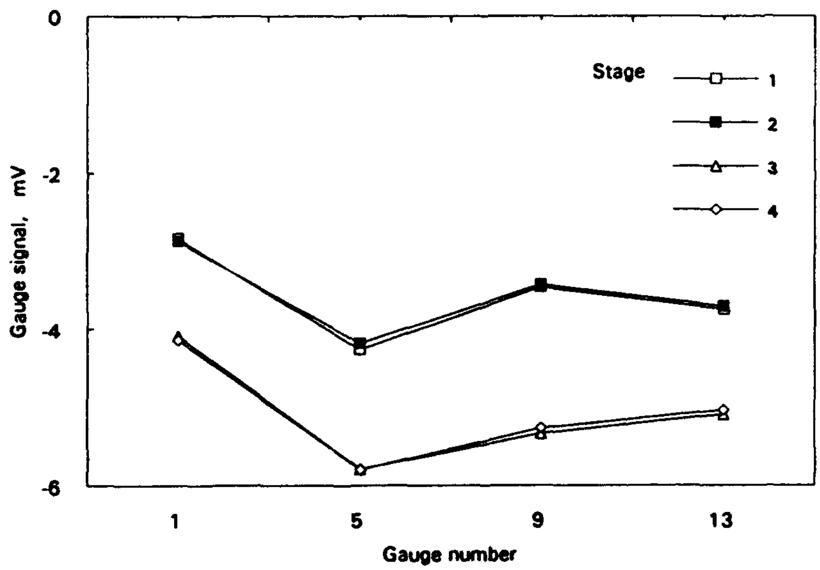

Figure 12: Zero load signals of welded longitudinal gauges L1G1, L1G5, L2G9 and L2G13. Note the changes in signals of the gauges from Stage 2 to Stage 3.

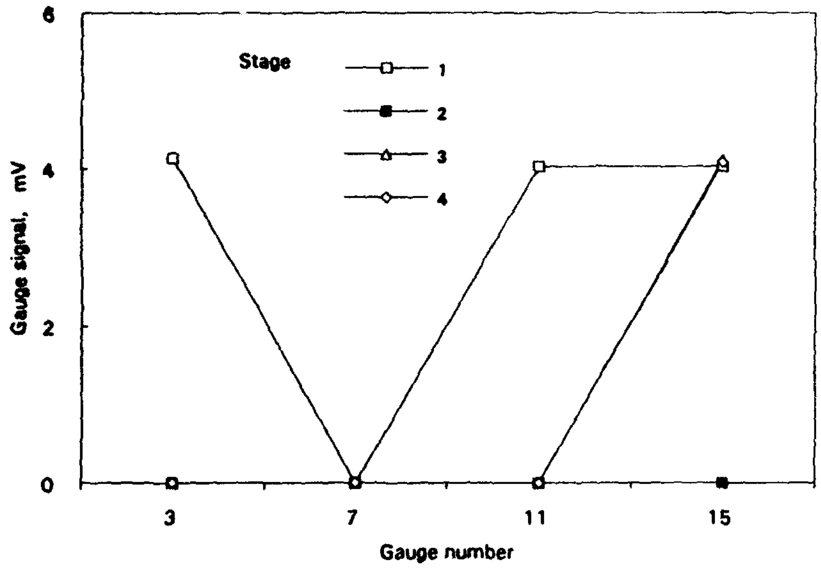

Figure 13: Span signals (0 to 125 kN) of adhesive longitudinal gauges L1G3, L1G7, L2G11 and L2G15. Spans of the gauges were not measured following Stage 2. Gauges L1G3 and L1G11 were unserviceable after Stage 2. Gauge L1G7 remained unserviceable after attachment. Note small changes in span for gauge L2G15 after each stage.

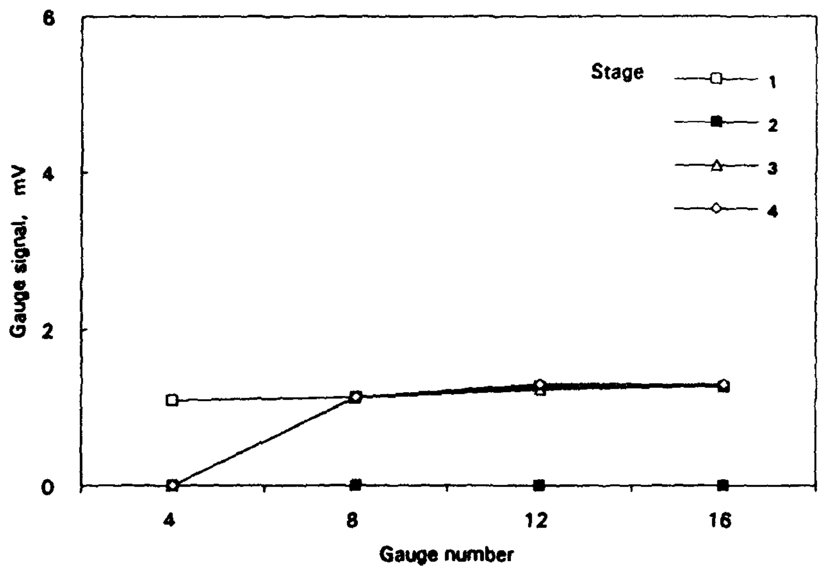

Figure 14: Span signals (0 to 125 kN) of adhesive transverse gauges L1G4, L1G8, L2G12 and L2G16. Spans of the gauges were not measured following Stage 2. Gauge L1G4 was unserviceable after Stage 2. Note the zero change in span for gauge L1G8 after each stage.

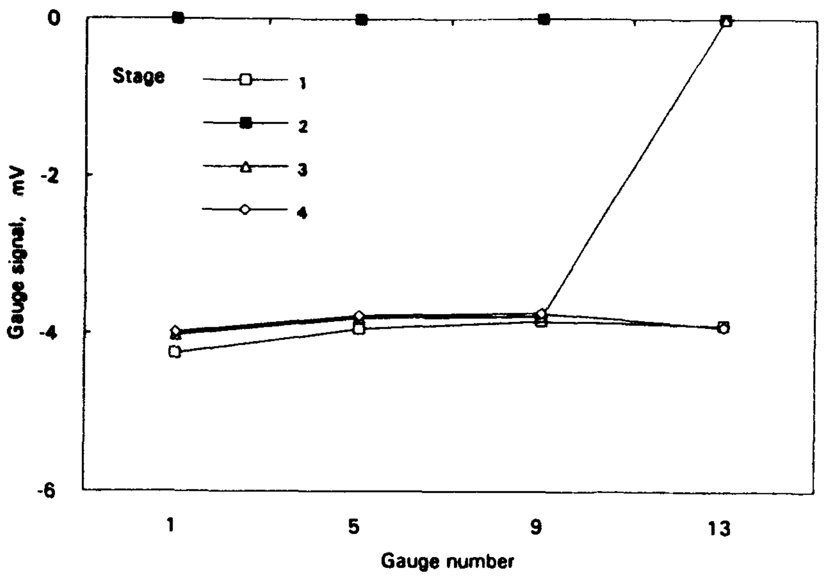

Figure 15: Span signals (0 to 125 kN) of welded longitudinal gauges L1G1, L1G5, L2G9 and L2G13. Spans of the gauges were not measured following Stage 2.

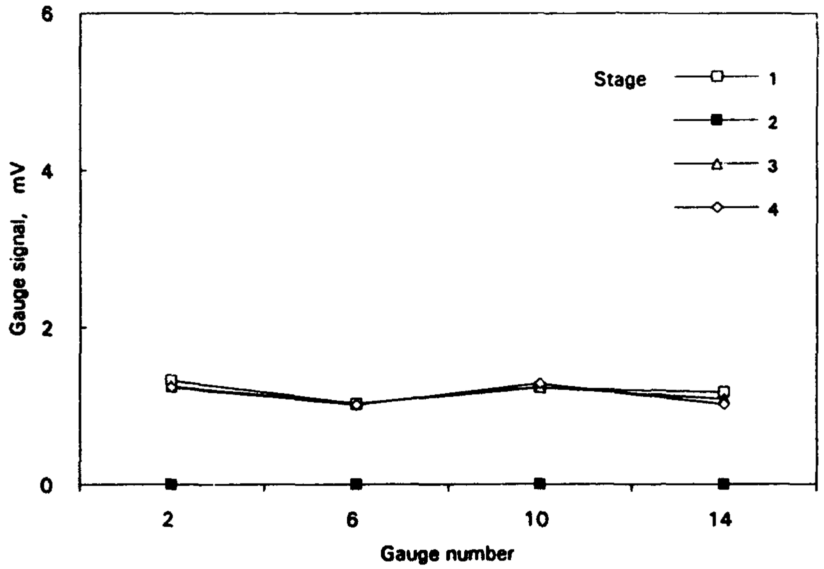

Figure 16: Span signals (0 to 125 kN) of welded transverse gauges L1G2, L1G6, L2G10 and L2G14. Spans of the gauges were not measured following Stage 2. Note zero change in span of gauge L1G6 after each stage.

4.2.1 *Stage 1 - After Installation of Gauges.*

In the installed condition and following the post cure, with the exception of gauge L1G7 (adhesive, longitudinal), all the remaining gauges were found to be functioning and recording consistent zero load and span signals, Tables 5 to 12. Examination of the data in Tables 9 to 12 shows that the ratio of transverse to longitudinal gauge signals, when the plate was loaded to a maximum of 125 kN, is approximately 0.3 and hence satisfies the Poisson's ratio and further attests to the accuracy of the gauges.

4.2.2 *Stage 2 - After Protective Coating*

In this stage, only the zero load bridge signals of the strain gauges were measured. The results are summarised in Tables 5 to 8 together with the changes in signals from Stages 1 and 2 in terms of equivalent stress. These changes were small and occurred in both positive and negative directions. With the exception of gauge L2G15, signal changes were ± 2 MPa for adhesive strain gauges and by comparison + 6 to - 1 MPa for weldable gauges. The large signal change in gauge L2G15 was due to an inadvertent polarity change, the correct signal change would be 1.5 MPa instead of 104 MPa. The gauge subsequently performed satisfactorily for the remainder of the tests.

4.2.3 *Stage 3 - After 48 hours at 300/200°C (First Thermal Cycling Experiment)*

Thermal cycling was carried out to determine the survivalibility of the strain gauges. It was intended to heat the plate to a maximum temperature of 200°C for 48 hours. This temperature is well above the minimum preheat temperature recommended for the welding procedure for Collins Class submarine structure, and is below the recommended maximum operating temperatures for the strain gauges, adhesive and the protective coating. However, due to the failure of the controller during the heating process, the plate temperature peaked at 300°C for approximately 30 minutes. After rectifying the heating controller the temperature was reduced to 200°C and then maintained at this level for 48 hours as originally planned.

Following the completion of the 48 hours thermal cycle, the strain gauges were reconnected to the data acquisition unit and the changes in zero load and span signals were measured. All the weldable strain gauges were found to be functioning, although significant changes in zero load signals were recorded. The reason for these changes may be due to their short exposure at 300°C.

Of the seven adhesive strain gauges reported working in Stages 1 and 2, another one, gauge L1G4, was not functioning after this thermal treatment. There were significant zero load signal shifts from Stage 2 to Stage 3, as shown in Tables 5 to 8. The maximum positive and maximum negative changes in zero load signals measured for the adhesive gauges were 57 MPa (L2G11) and 40 MPa (L1G8) respectively. Only negative changes in zero load signals were recorded for the weldable strain gauges, Tables 7 and 8, with the maximum change of - 80 MPa recorded by gauge L2G9.

The span signals measured following the thermal cycling are shown in Tables 9 to 12. Comparing data from Stage 1 and Stage 3, it was found that the changes in the span signals for the adhesive strain gauges were small; a maximum positive change of 4 MPa occurred for gauge L2G15 and a negative maximum change of 1.5 MPa was observed in gauge L2G12. For the weldable strain gauges the maximum changes in the span signals, between Stages 1 and 3, were + 10 MPa (L1G1) and - 4 MPa (L2G14) respectively.

4.2.4 Stage 4 - After 2 hours at 200°C (Second Thermal Cycling Experiment)

This second thermal cycling experiment was to determine if the changes in zero load signals and span signals recorded after Stage 3 were the result of the maximum temperature exceeding 200°C. The thermal cycle was for 2 hours at 200°C after which zero load and span signals were measured. Tables 5 to 8 show the zero load signals recorded after Stage 4. Two longitudinal adhesive strain gauges (L1G3 and L2G11) were no longer functioning, however all the weldable strain gauges were found to be working satisfactorily. Of the remaining adhesive gauges, gauge L2G15 recorded a maximum positive zero load signal change of 1 MPa and gauge L2G16 recorded a maximum negative change was 5 MPa (cf. Stages 3 & 4). These results suggest that the changes in gauge signals were insignificant provided the temperature limitations of the gauges and adhesive system were not exceeded.

Further experiments involving thermal cycling were carried out using new gauges mounted on a separate block of steel. The steel block was subjected to thermal cycles ranging between 150 to 200°C for a 24 h period. At the end of each cycle the zero load signals were measured and the changes recorded. Once again two out of the four adhesive gauges performed unreliably, while the other two recorded zero load signal changes between 8 to 10 MPa. All the weldable gauges performed well and recorded zero load signal changes between 3 to 11 MPa. These results again showed that the gauge signal stability and adhesion could not be fully assured even when care was taken in not exposing them to temperatures higher than those specified.

The span signals for adhesive gauges are listed in Tables 9 and 10. It is interesting to note that the gauge L2G16, which recorded a change in the zero load signal of - 23 MPa from Stage 1 to Stage 3 (Table 6), registered no change in its span signal. This shows that the gauge is still capable of accurately measuring applied stresses. Of the four adhesive strain gauges, gauge L2G12 showed a maximum positive span signal change of 3 MPa (Stage 4, Table 10), whereas a maximum negative span signal change of 1 MPa was observed in gauge L2G15 (Stage 4, Table 9).

All weldable strain gauges were found to be functional following the second thermal cycle (Stage 4). Tables 7 and 8 show the zero load signals recorded for this stage. Comparing these results with those in Stage 3, a maximum positive change of 3 MPa was recorded for gauge L2G9, whereas a maximum negative change of 5 MPa was observed in gauge L2G14.

The changes in span signals for the weldable gauges are listed in Tables 11 and 12 (Stage 4). Results showed that changes in span signals were small and ranged between + 2 MPa to - 3 MPa.

4.2.5 *Gauge Calibration*

The strain gauges were calibrated by subjecting the plate to a four point bending load. The signals after each of the four stages are shown in Tables 9 to 12. From §3.3.4, a 125 kN load should, from simple beam theory, create a 172 MPa stress at the outer fibre, i.e. at the gauge centreline. From Tables 9 and 11, the average change in signal due to a 125 kN load for the longitudinal gauges was approximately 4.0 mV. Therefore, each 1 mV change is equivalent to a stress change of 43 MPa, i.e. gauge sensitivity = 43 MPa/mV

4.2.6 *Stages 5 to 9*

Stages 5 to 9 correspond to individual welding passes at distances ranging from 200 mm up to 50 mm (Table 3). Stage 9 corresponds to a second welding pass at a distance of 50 mm from the gauge centreline. At the completion of each welding pass, gauges were reconnected to the data acquisition system to measure and record the cumulative change in each gauge signal. The results are presented in Tables 13 to 16 and illustrated in Figures 17 to 20.

The results showed that gauges which were functioning at the end of Stage 4, recorded the build-up of residual stresses due to the welding passes in Stages 5 to 9. Generally, high cumulative residual stresses were recorded by the transversely oriented gauges and were twice the magnitude of those recorded by longitudinally oriented gauges, e.g gauges L2G10 and L1G5. These gauges were located away from the edges. In contrast, for strain gauges located close to the edge, lower cumulative residual stresses were recorded and the magnitude registered by transverse gauges was over five times that registered by longitudinal gauges, eg. L2G16 and L2G15. These two trends suggested (a) weld induced shrinkage stresses were greater in the welding direction (the transverse direction of the plate) and (b) strong edge effects.

Table 5: *Zero load signals of longitudinal adhesive gauges*

	L1G3		L1G7	L2G11		L2G15	
	mV	ESC(1)	mV	mV	ESC	mV	ESC
Stage 1	- 0.93	0	US(2)	- 1.912	0	- 1.192	0
Stage 2	- 0.897	1	US	- 1.914	0	1.228	104
Stage 3	0.112	43	US	- 0.575	57	1.807	25
Stage 4	US		US	US		1.828	1

(1) ESC is the Equivalent Stress Change in MPa recorded for each experimental stage.
(2) Unserviceable.

Table 6: Zero load signals of transverse adhesive gauges

	L1G4		L1G8		L1G12		L2G16	
	mV	ESC	mV	ESC	mV	ESC	mV	ESC
Stage 1	1.335	0	0.513	0	- 2.858	0	- 3.252	0
Stage 2	1.383	2	0.548	1	- 2.853	0	- 3.299	-2
Stage 3	US		- 0.372	- 40	- 3.574	- 31	- 3.843	- 23
Stage 4	US		- 0.448	- 3	- 3.654	- 4	- 3.959	- 5

Table 7: Zero load signals of transverse welded gauges

	L1G2		L1G8		L2G10		L2G14	
	mV	ESC	mV	ESC	mV	ESC	mV	ESC
Stage 1	- 2.572	0	- 3.99	0	- 2.613	0	- 3.525	0
Stage 2	- 2.471	4	- 3.963	1	- 2.477	6	- 3.506	1
Stage 3	- 3.613	- 49	- 5.471	- 63	- 3.533	- 45	- 4.556	- 45
Stage 4	- 3.642	- 1	- 5.460	0	- 3.539	0	- 4.665	- 5

Table 8: Zero load signals of longitudinal welded gauges

	L1G1		L1G5		L2G9		L2G13	
	mV	ESC	mV	ESC	mV	ESC	mV	ESC
Stage 1	- 2.835	0	- 4.264	0	- 3.458	0	- 3.746	0
Stage 2	- 2.884	- 1	- 4.184	3	- 3.425	1	- 3.704	2
Stage 3	- 4.082	- 51	- 5.787	- 67	- 5.339	- 80	- 5.098	- 59
Stage 4	- 4.139	- 2	- 5.796	0	- 5.273	3	- 5.044	2

Table 9: Span signals of longitudinal adhesive gauges

	L1G3		L1G7		L1G11		L2G15	
	mV	ESC	mV	ESC	mV	ESC	mV	ESC
Stage 1	4.138	0	US		4.033	0	4.031	0
Stage 2	-		-		-		-	
Stage 3	US		US		US		4.117	4
Stage 4	US		US		US		4.086	- 1

Table 10: Span signals of transverse adhesive gauges

	L1G4		L1G8		L1G12		L2G16	
	mV	ESC	mV	ESC	mV	ESC	mV	ESC
Stage 1	1.09	0	1.133	0	1.270	0	1.288	0
Stage 2	-		-		-		-	
Stage 3	US		1.128	0	1.235	- 2	1.275	0
Stage 4	US		1.130	0	1.305	3	1.296	1

Table 11: Span signals of longitudinal welded gauges

	L1G1		L1G5		L2G9		L2G13	
	mV	BSC	mV	BSC	mV	BSC	mV	BSC
Stage 1	- 4.252	0	- 3.944	0	- 3.844	0	- 3.896	0
Stage 2	-		-		-		-	
Stage 3	- 4.018	10	- 3.801	6	- 3.781	3	US	
Stage 4	- 3.986	1	- 3.777	1	- 3.740	2	- 3.920	- 1

Table 12: Span signals of transverse welded gauges

	L1G2		L1G8		L2G10		L2G14	
	mV	BSC	mV	BSC	mV	BSC	mV	BSC
Stage 1	1.322	0	1.023	0	1.226	0	1.172	0
Stage 2	-		-		-		-	
Stage 3	1.249	- 3	1.023	0	1.234	0	1.086	- 4
Stage 4	1.233	- 1	1.012	0	1.282	2	1.021	- 3

Table 13: Welding trials-zero load signals of longitudinal weldable gauges

Stage	Gauge Distance mm	L1G1 Signal/Change mV/MPa	L1G5 Signal/Change mV/MPa	L2G9 Signal/Change mV/MPa	L2G13 Signal/Change mV/MPa
		- 4.491/0	- 6.084/0	- 5.481/0	- 5.407/0
5	200	- 4.428/3	- 6.103/-1	- 5.427/2	- 5.264/6
6	150	- 4.324/7	- 6.124/-2	- 5.525/-2	- 5.513/4
7	100	- 8.881/-189*	- 6.291/-9	- 5.755/-12	- 5.365/2
8	50	- 6.999/-108*	- 6.706/-27	- 6.246/-33	- 5.778/-16
9	50	- 4.385/5	- 6.843/-33	- 6.298/-35	- 5.861/-20

* Unexplained

Table 14: Welding trials-zero load signals of transverse weldable gauges

Stage	Gauge Distance mm	L1G2 Signal/Change mV/MPa	L1G8 Signal/Change mV/MPa	L2G10 Signal/Change mV/MPa	L2G14 Signal/Change mV/MPa
		- 3.880/0	- 5.661/0	- 3.714/0	- 5.009/0
5	200	- 3.677/9	- 5.364/13	- 3.452/11	- 4.751/11
6	150	- 3.543/14	- 5.145/22	- 3.335/16	- 4.501/22
7	100	- 3.748/17	- 4.760/39	- 2.920/34	- 4.262/32
8	50	- 3.292/25	- 4.187/63	- 2.362/58	- 3.590/61
9	50	- 3.139/32	- 4.038/70	- 2.281/62	- 3.228/77

Table 15: *Welding trials-zero load signals of longitudinal adhesive gauges*

Stage	Gauge Distance mm	L1G3 Signal/Change mV/MPa	L1G7 Signal/Change mV/MPa	L2G11 Signal/Change mV/MPa	L2G15 Signal/Change mV/MPa
				- 0.575/0	2.040/0
5	200	US	US	- 0.294/12	2.027/-0.5
6	150	US	US	- 0.564/0.5	1.871/-7
7	100	US	US	- 0.547/1	1.780/-11
8	50	US	US	- 0.589/0	1.820/-9
9	50	US	US	- 0.488/6	1.864/-8

Table 16: *Welding trials-zero load signals of transverse adhesive gauges*

Stage	Gauge Distance mm	L1G4 Signal/Change mV/MPa	L1G8 Signal/Change mV/MPa	L2G12 Signal/Change mV/MPa	L2G16 Signal/Change mV/MPa
			- 0.650/0	- 3.911/0	- 4.258/0
5	200	US	- 0.449/9	- 3.692/9	- 4.101/7
6	150	US	- 0.108/23	- 3.390/22	- 4.035/10
7	100	US	0.238/38	- 3.017/38	- 3.941/14
8	50	US	0.828/64	- 2.382/65	- 3.613/28
9	50	US	0.911/67	- 2.105/78	- 3.431/36

4.3 *Effect of Spot Welding on Fatigue Life*

When a smooth circular hourglass shape RQT 701 steel specimen (similar to BIS 812 EMA steel) and with spot welds located around the minimum diameter was fatigue tested at maximum cyclic stress of 753 MPa, fatigue failure resulted after 33,000 cycles. Repeating the test on a plain specimen (no spot welds) resulted in a test run-out after 110,000 cycles. The high input energy associated with the laying of spot welds creates brittle areas at microscopic levels. These areas add to the existing stress concentration and when subjected to fatigue loading result in early crack initiation. Scanning electron microscopy of fractured specimen showed brittle intergranular fracture at or near spot welds. Results from these fatigue tests indicate that when spot welds are used to attach weldable strain gauges at or near stress concentrations early fatigue crack initiation may result. In order to overcome this problem, attachment of weldable gauges at such locations must be avoided, and monitoring of stress 'shake-down' at designated highly stressed locations in a submarine structure should be carried out by post weld installation of adhesive strain gauges.

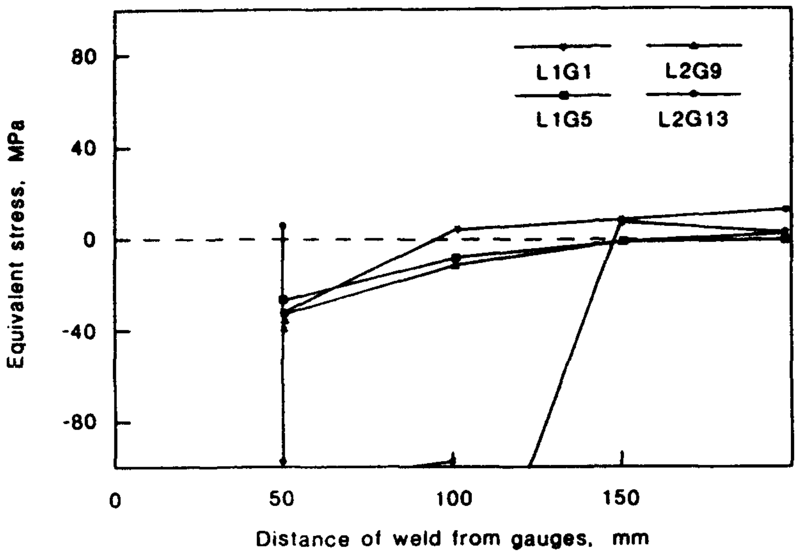

Figure 17: Weld induced stresses measured by welded longitudinal gauges. The reason for the unusual behaviour of gauge L1G1 was not known.

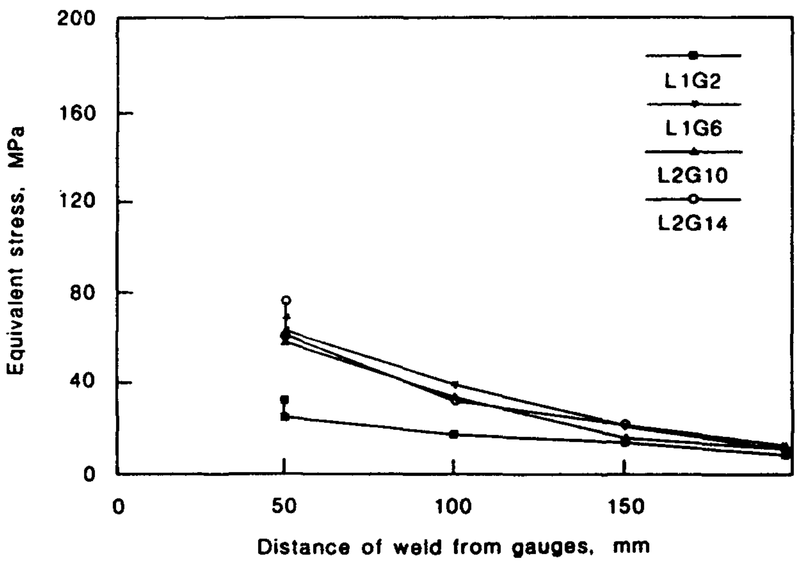

Figure 18: Weld induced stresses measured by welded transverse gauges. Note the increases in the induced stress due to the second weld pass at a distance of 50 mm.

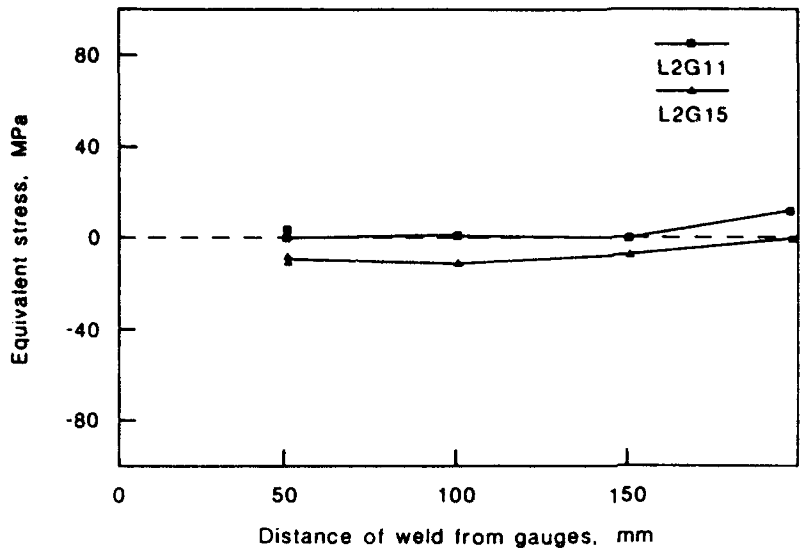

Figure 19: Weld induced stresses measured by adhesive longitudinal gauges.

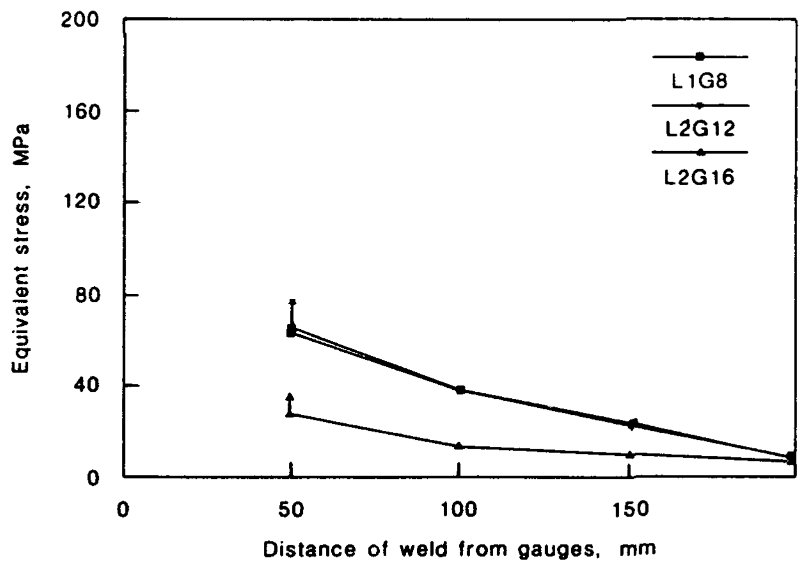

Figure 20: Weld induced stresses measured by adhesive transverse gauges. Note the increases in the induced stress due to the second weld pass at a distance of 50 mm.

5. Discussion

This study has shown that strain gauging of structural details of the Collins Class submarine structure for residual stress measurement (and condition monitoring) is possible, and the experimental methodology described in this report can, with some modifications, be developed and applied to submarine hulls during construction. As expected, the accuracy of strain measurement is heavily dependent upon the proper installation of strain gauges. This has been highlighted by the present study; particularly for the strain gauges which use adhesives and where adverse environmental conditions prevail, as discussed below.

The use of strain gauging to determine the response of ship structures is a relatively common practice, many systems which utilise this type of technology are in operation in commercial vessels, see for example Shah-Khan *et al.* (1993) and MER (1991). These strain gauges can be foil gauges, such as used in the present study, or fibre-optic gauges, Rogers (1988) and Turner *et al.* (1990). The gauges are used to monitor the levels of strain developed in critical areas of ship structures (see for example Chiou *et al.* (1990)). Additionally, considerable experience in the use of adhesive gauges has been gained during the hydrodynamic load trials of a Destroyer Escort, HMAS Swan, Elischer *et al.* (1992a & b). Strain gauging has also been used to measure the levels of residual stress developed in welded ship and submarine structures. The use of adhesive gauges has been reported by Smith and Kilpatrick (1991).

The two types of gauges assessed in the present work were adhesive gauges and weldable gauges. The work clearly showed that the weldable gauges exhibited a high degree of reliability during the temperature cycles. The adhesive gauges exhibited a substantial number of failures following thermal cycles and their signal reliability was found lower than weldable gauges. This poor performance of the adhesive gauges was not exhibited in the work reported by Elischer (1992a & b), but in that task the adhesive gauges were not subjected to the extreme temperature range used in the present experiments.

The poor performance, as observed in the initial and later experiments, of the adhesive gauges is of some concern and additional experimental work to improve the integrity of gauges during installation is required. The weldable gauges on the other hand appear to be suitable for studies involving residual stress measurements in the submarine hull structure. The signal stability of the weldable gauges through the temperature cycling which simulated plate pre-heating has been demonstrated. Weldable strain gauges have an advantage over the adhesive gauges in that they are easier to handle and install. For high temperature application the adhesive requires high temperature curing and post curing processes which create some technical difficulties during gauge installation, particularly on large structures. Weldable strain gauges have another clear advantage in that damaged or inoperative weldable gauge can be easily replaced without the need for the difficult installation procedure associated with the adhesive strain gauges.

However weldable gauges suffer from one significant disadvantage and that is the microstructural damage imparted to the material by the array spot welds. The results are consistent with the observations of Harkasson and Dixon (1992) who showed that weld strikes produce a decrease in fatigue life. However, welded strain gauges are still appropriate for the measurement of residual stress and where gauges are removed following residual stress determination, the damage to the surface can be removed by light grinding (similar to the restoration applied to the plate after the removal of thermocouple wires). Although first indications are that welded gauges are detrimental in regions of high stresses further experimental investigation of this effect is desirable.

Two important signal characteristics of the strain gauges studied in this report, namely zero load and span signals, showed changes following thermal cycles. A temperature of 300°C even for a short period of 30 minutes caused significant shifts in their zero load signals. Comparatively, the span signals were only marginally effected. Small shifts in the span signals indicate that the strain gauges were capable of measuring strains even when exposure temperature was as high as 300°C. Such high temperatures are, however, not appropriate for strain gauges and the adhesive. Thermal cycling to a temperature of 200°C caused negligible changes in both the zero load and span signals of the strain gauges.

Figures 21 and 22 were constructed in order to provide an easy reference to the history of results obtained in experiments. Figure 21 represents the history of signals in Equivalent Stress (MPa) for gauge L2G13. Events 1 to 8 correspond to signals measured after each resoldering (Table 4). The signals measured during the calibration of the above gauge are represented by events 10 to 15. Events 16 and 17 correspond to measurements after each thermal cycle. Measurements after each welding pass are represented by events 18 to 22. This history graph is typical of a good, well bonded gauge because the slope of the graph represented by events 18 to 22 is in the same direction as the calibration part of the graph (events 10 to 15). The combined history of zero load signals for four gauges is shown in Figure 22. On the x-axis, events 9 to 22 are registered in the same sequence as mentioned above. Two longitudinal and two transverse gauges of either type were selected for this graph. With the exception of adhesive longitudinal gauge L2G15, the remaining three gauges measured changes in zero load signals due to welding (events 18 to 22).

The strain gauging methodology investigated can be extended to measure residual stresses for through life monitoring. The life of installed gauges in this environment and the data acquisition systems would need to be addressed in a separate program. An extended strain gauging program would provide a unique opportunity to study the changes in stress states at a number of locations within the submarine structure during its operation. The "shake-down" of residual stresses (and consequent effect on crack growth rates) would be accommodated within life prediction models.

The success of long-term monitoring programs would, of course, be dependent upon the identification of appropriate regions for monitoring. Those regions which are inherently high in stresses or those which are under high operating stresses would need to be identified. Some regions have been identified by an inspection of the structural details of the submarine and are summarised in Appendix 1.

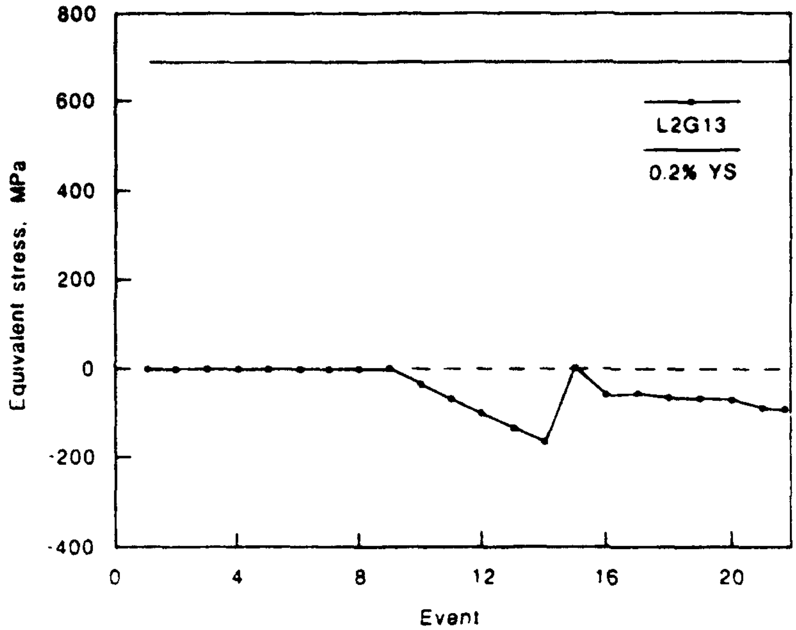

Figure 21: History (signals) of a welded longitudinal gauge L1G13. Events 1 to 8 correspond to solder/resolder. Events 9 to 15 correspond to gauge calibration (span). Events 16 and 17 correspond to thermal cycles. Events 18 to 22 correspond to weld passes as mentioned in the text.

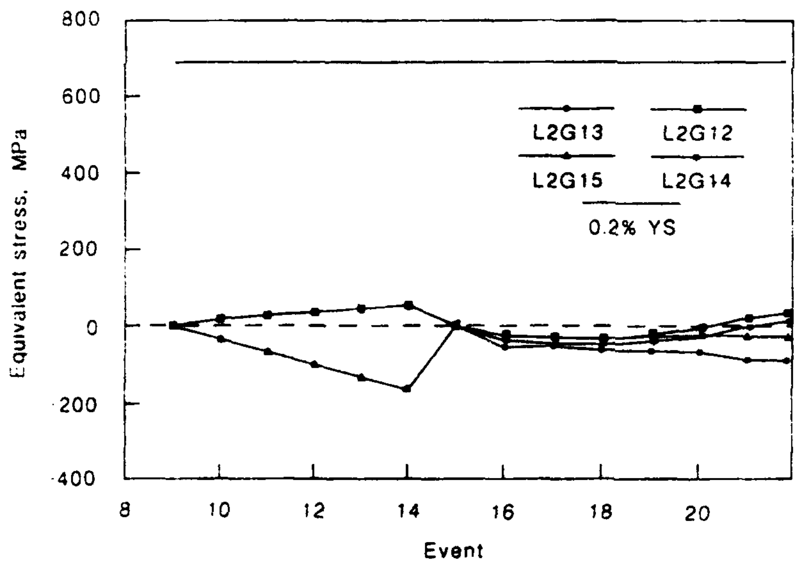

Figure 22: Combined history (signals) of gauges. The sequence of the events is the same as in Figure 21.

6. Conclusions

The study undertaken has shown that stress monitoring in a structure can be carried out by the use of strain gauges. Of the two types of strain gauges studied in the present work, the welded strain gauges were found more suitable than adhesive gauges in terms of (a) ease of installation and (b) survivability when exposed to high temperature.

6.1 It was found that installation procedure for adhesive strain gauges required extreme care and incorrect procedures can result in inoperative gauges. The adhesive requires curing under specified pressure and temperature. Post-curing is also required at specified temperatures. In comparison, the welded strain gauges were found to be relatively simple to install and do not require curing.

6.2 The survivability of gauges and adhesive in environments likely to be encountered during submarine construction and operation is a major concern. Thermal cycling of the gauges has shown that the survivability of adhesive gauges was lower than weldable gauges.

6.3 The protective coating survived the high temperatures (300°C) to which it was exposed. The coating protected the gauges from ambient conditions and welding sparks during the welding process. The protective coating is similar to that used by MRL in the hydrodynamic load trials of the HMAS SWAN wherein the coating was found to have survived harsh service conditions including saline and humid environments. Additional work would need to be undertaken to explore other types of protective coatings available for their suitability.

6.4 The study has shown that two important strain gauge characteristics appropriate to residual stress measurements in submarines namely, the zero load and span signals, changed after each stage of the experiment, however these changes were small. The changes in zero load signals, when converted into equivalent stress, were a good indication of the build up of residual stresses in a structure. Reliability in the strain gauge measurements was found to be high for the welded gauges whereas, the adhesive gauges exhibited poorer reliability and were found to be more sensitive to thermal cycling.

6.5 The transversely oriented strain gauges recorded high cumulative residual stresses which were twice the magnitude of the stresses recorded by longitudinally oriented gauges. Lower cumulative residual stresses were recorded at the edges of the test plate. The results suggest (a) weld induced shrinkage stress is greater in the welding direction (the transverse direction of the plate) and (b) there are strong edge effects.

6.6 Spot welding the weldable gauges in regions of high stress concentration definitely contributes to early fatigue crack initiation. For residual stress measurements at locations of high stress concentration, the adhesively bonded gauges should be used. At other locations the welded gauges should be considered.

7. Acknowledgement

The authors wish to acknowledge Mr. S. Anstey (Engineering Support Division) for instumentation assistance, Mr. P. P. Elischer (Scientific Support Division) for a thorough review of this report and Dr. R.L. Woodward (Ship Structures and Materials Division) for constant encouragement during this study.

8. References

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Appendix 1

The Strain Gauging Program

The proposed program is an extension of an earlier Research Proposal of Shah-Khan (1992) and provides an excellent opportunity to follow the development and modification of residual stress levels in a large defence platform. Additionally, strain gauging itself provides a convenient method for condition monitoring of the submarine structure over long periods of time. Changes in the strain distribution in the structure can be used in damage analyses such as crack growth, distortion and/or progressive failure of attached structure and/or components. Strain gauging, then, can be a part of a damage tolerance and defect analysis methodology for the submarine.

The residual stress data obtained from the experiment(s) can be incorporated into fatigue life prediction methodologies thus permitting an accurate quantitative assessment of the behaviour of the submarine structure under service loading conditions. The proposed program would also be of long-term defence relevance because it would provide appropriate data on the changes of stress states within the structure during service. The monitoring of fatigue loading effects in submarine hulls is the first step in the development of "smart structures" for Naval applications. It is considered that the residual stress measurement and strain monitoring during service is appropriate for the Type 471 submarine because the submarine is a "high cost" item.

Depending upon the number of submarine hulls and individual sites which are strain gauged, the costs of the program should be able to be estimated with considerable accuracy, see for example the preliminary estimates of Wells et al. (1991). Most importantly, however, the program requires extreme care and planning for it to be fully effective. The ultimate success of the program will depend upon the selection of representative sites in the submarine structure(s), the preservation of the gauges and wiring throughout the fabrication and fitting processes and the development of a data logging system suitable for strain monitoring over long periods of time once the Type 471 submarine enters service with the Australian Navy.

In conjunction with this program, MRL is involved in the development of fatigue damage modelling of the submarine structure (or sections which are identified as more susceptible to fatigue than others). Information derived from the strain gauging exercise would be used within the fatigue model to allow more accurate prediction of submarine life. Subsequent measurements of residual stress during service will enable the determination of a modified stress intensity factor which would, ideally, give a better indication of service life.

The initial stages of the strain gauging program will be to identify regions in which high residual stresses could develop during fabrication and service and where strain gauges can be fitted. These locations should be areas where no other fittings, etc., are likely to be attached, enabling the gauges to be preserved throughout the construction process and providing ready access when construction is completed. Several sites (Table A-1) are considered suitable for strain gauging. These locations should produce representative residual stress information.

Table A-1: Hull Locations for Strain Gauging

	REGION	FRAME NUMBER
FORWARD LOCATION		
- CAN WITH RING STIFFENERS AND BULKHEADS	7450-9815	14
- CAN WITH RING STIFFENERS	9815-12100	20
- CAN WITH RING STIFFENERS AND PENETRATION	14010-17800	32
- CAN WITH RING STIFFENERS AND DEEP FRAME	17800-20160	37
MIDDLE LOCATION		
- CAN WITH RING STIFFENERS	28305-31275	57
- CAN WITH RING STIFFENERS BULKHEADS AND PENETRATION	37075-40090	72
- CAN WITH RING STIFFENERS AND DEEP FRAME	45035-47135	89
AFT LOCATION		
- CAN WITH RING STIFFENERS	55235-57960	105
- CAN WITH RING STIFFENERS AND DEEP FRAME	57960-60895	115
- CAN WITH RING STIFFENERS AND BULKHEAD	65515-67315	127

The sites must be accessable throughout fabrication. The sealing and preservation of the strain gauge system throughout the welding fabrication and completion of the submarine is an essential part of this program and MRL is currently investigating a number of methods. It is considered that the gauges and/or adhesives should have a functional life in excess of 5 years. This presents demanding requirements for the protection of the gauges.

Additional experimental work would be undertaken to detemine the long-term stability of the strain gauging system.

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SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-TR-93-8	AR-008-265	Unclassified

TITLE

An investigation of the potential for residual stress measurements during submarine hull fabrication

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REPORT DATE	TASK NO.	SPONSOR
September, 1993	DST 91/234	DSTO
FILE NO.	**REFERENCES**	**PAGES**
G6/4/8-4450	33	42

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY
Chief, Ship Structures and Materials Division

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Stress Measurements Strain Gauges Welding Construction

ABSTRACT

In this technical report the suitability of resistive strain sensors was evaluated with particular reference to the monitoring of residual stresses during welding construction of submarine pressure hull and during seabound operation of a submarine. Adhesively bonded and weldable strain gauges were tested in the laboratory for suitable characteristics and against specific requirements. The requirements were (a) ease of installation (b) survivability in high temperature environment (c) reliability in gauge signal and (d) ease of instrumentation to data logging system and calibration. Experiments which were designed to evaluate these requirements are described. The characteristics and fundamentals of the adhesive and weldable gauges explored during these experiments are discussed. Quantitative data in terms of strain gauge signal were determined following each stage of experimentation. The magnitude of strain gauge signal, when converted to equivalent stress units, provided an accurate measure of stress levels in the test plate. The results indicate that it is possible to implement structural monitoring starting from welding fabrication to service operation for the Collins Class submarine using resistive strain gauges.

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UNCLASSIFIED

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(MRL-TR-93-8)

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